Hot Structure

Nonlinear Thermal/Structural Analysis of Hypersonic Vehicle Hot Structures

NASA Workshop on Innovative
Finite Element Solutions to Challenging Problems
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Michael C. Lindell and Ruth M. Amundsen
Structural & Thermal Analysis Branch
NASA Langley Research Center
Hampton, Virginia

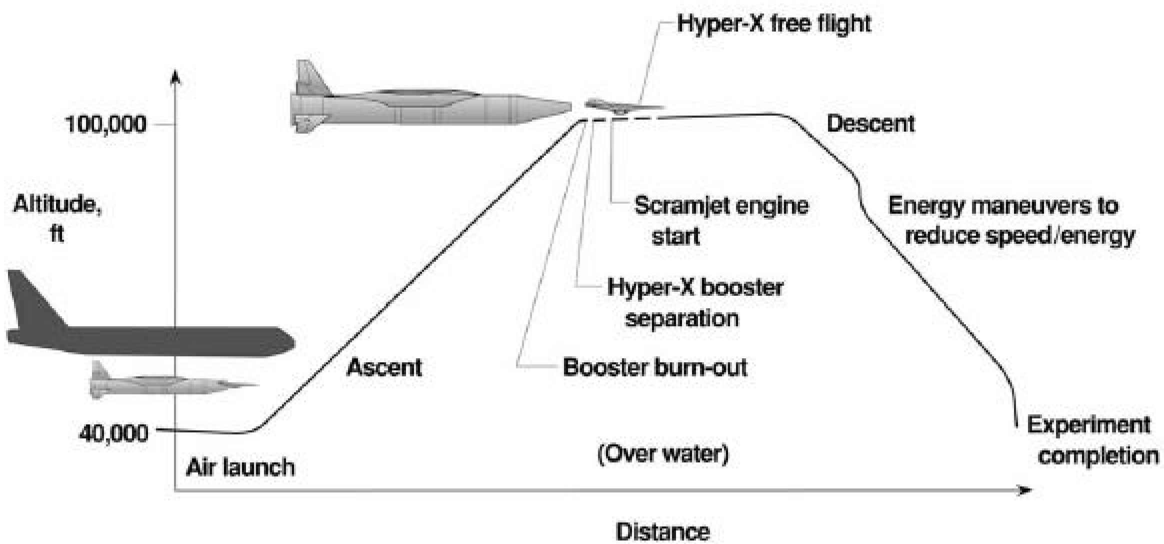
Outline

- Hyper-X Introduction
- Analysis Challenges
- Aero-Thermo-Structural Analysis Process
- Thermal Analysis Methods & Results
- Structural Analysis Methods & Results
- Conclusions

Hyper-X Introduction

- **Goal: To validate, in flight, propulsion and related technologies for air-breathing hypersonic aircraft.**
- **Product: Two vehicles capable of Mach 7 and one vehicle capable of Mach 10.**
- **Schedule: First Mach 7 flight in late 2000.**
- **Payoff: Increased payload capacities and reduced costs for future vehicles by eliminating on-board oxygen fuel requirements.**

HYPER-X FLIGHT TRAJECTORY



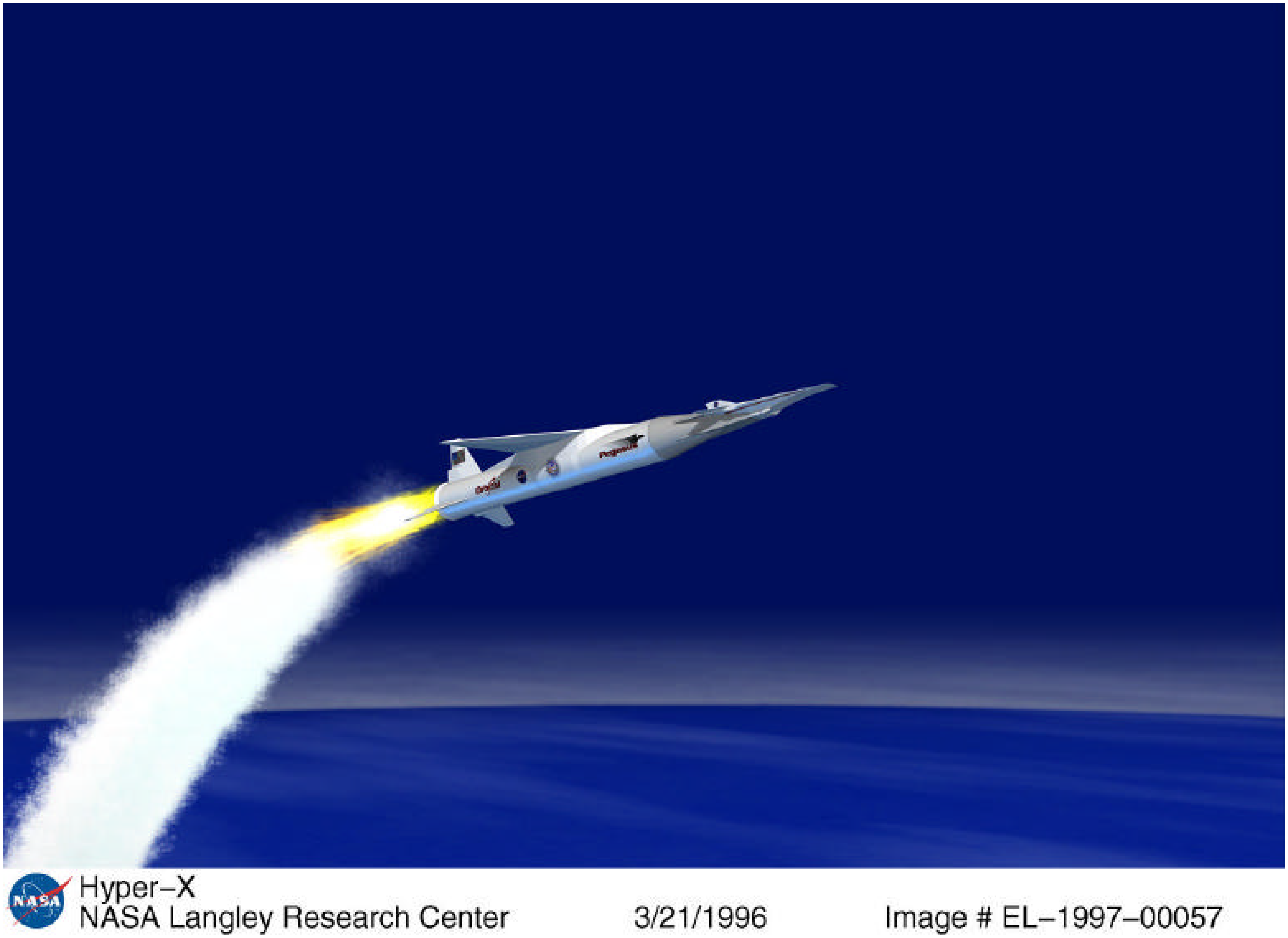
I/FYPR-X FLGHT TRJCTRY|Rausch

Hyper–X
NASA Langley Research Center 3/19/1997 Image # EL–1997–00029

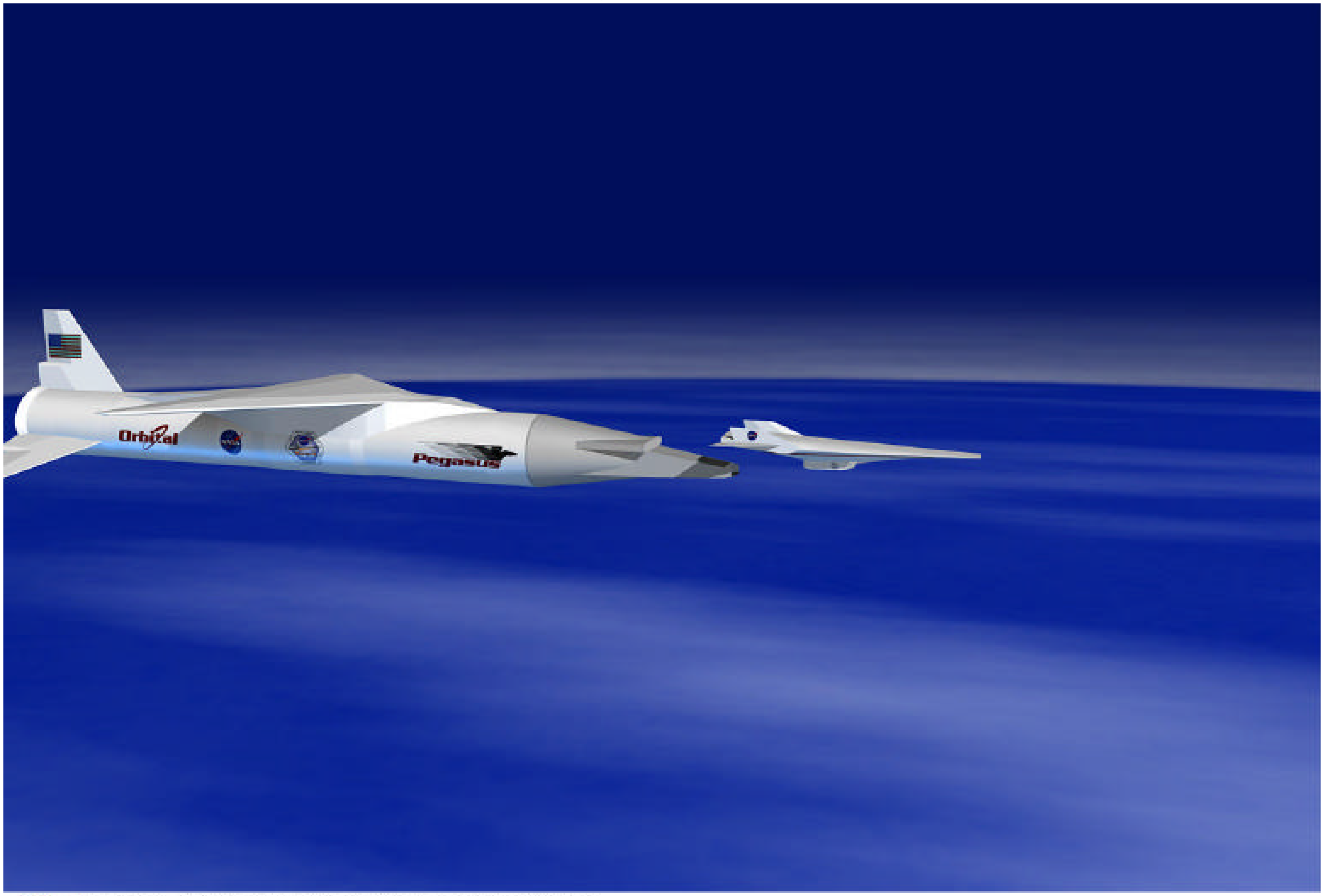
Hyper-X Vehicle and Booster on B-52

Hyper–X Flight Trajectory From Animation Video
NASA Langley Research Center 3/21/1996 Image # EL–1997–00023

Hyper-X During Pegasus Boost

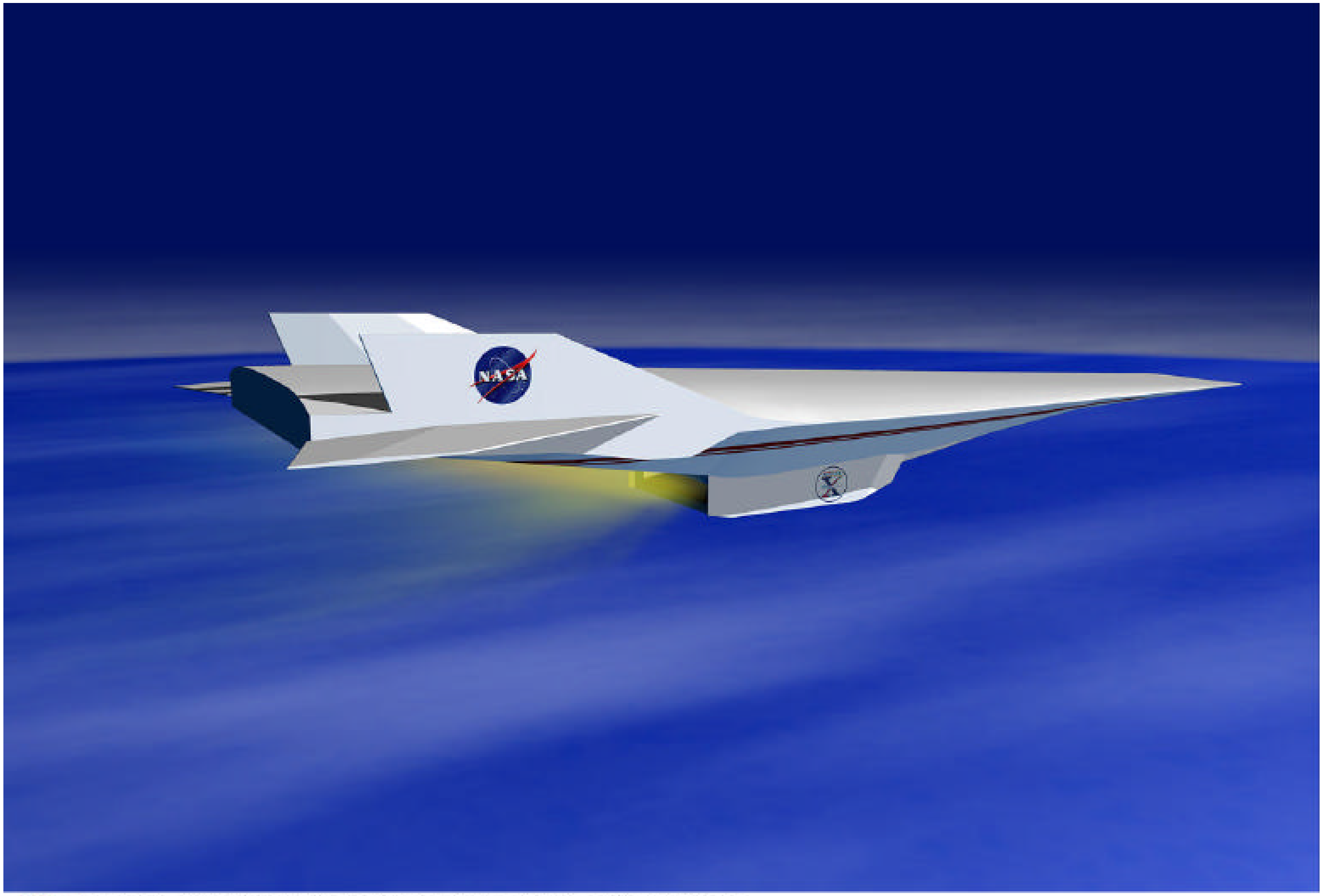


Hyper-X Separating for Free Flight



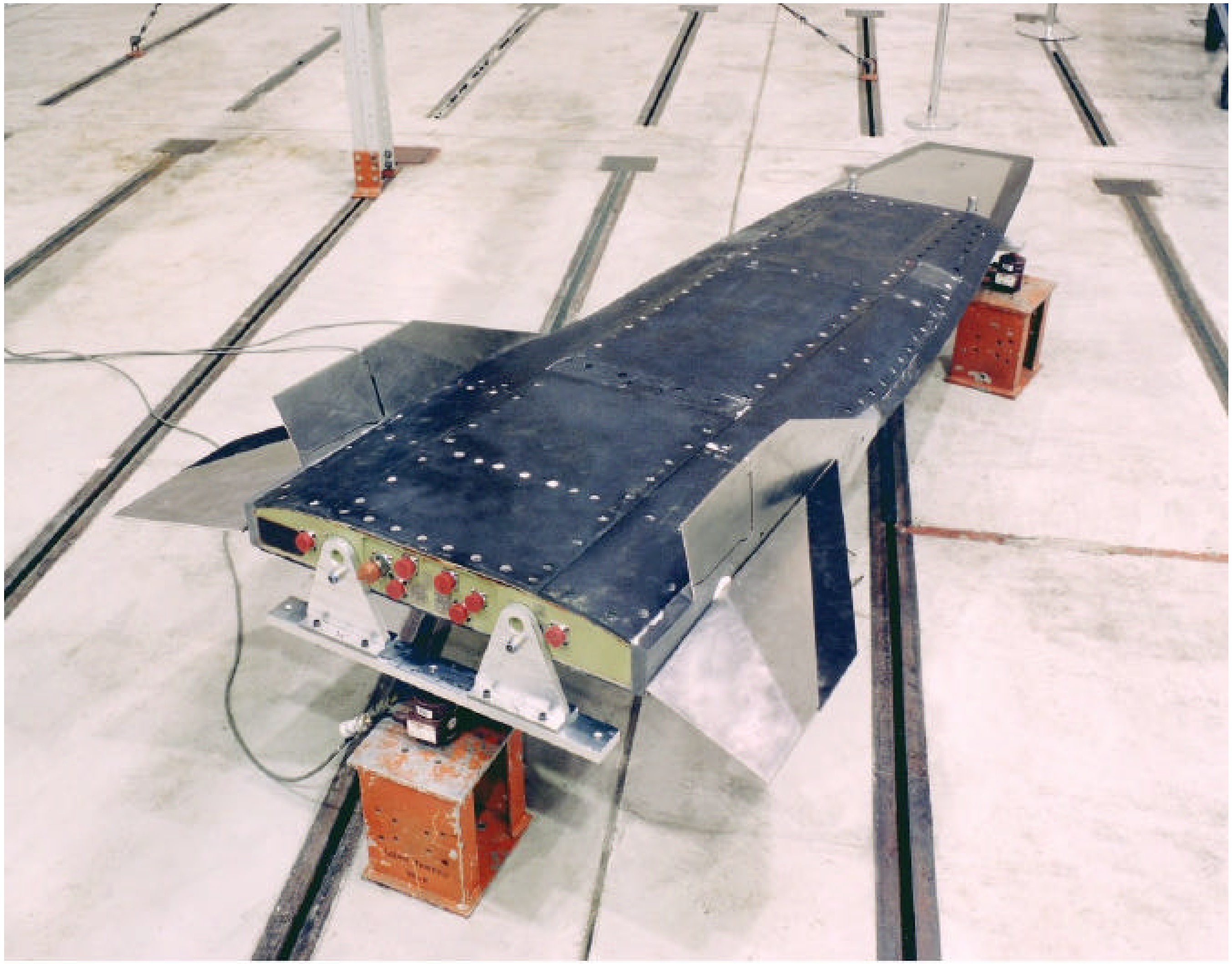
Hyper–X Flight From Animation Video
NASA Langley Research Center   3/21/1996   Image # EL–1997–00060

Hyper-X Engine Test



Hyper–X Flight Trajectory From Animation Video
NASA Langley Research Center 3/21/1996 Image # EL–1997–00024

Hyper-X Flight Hardware

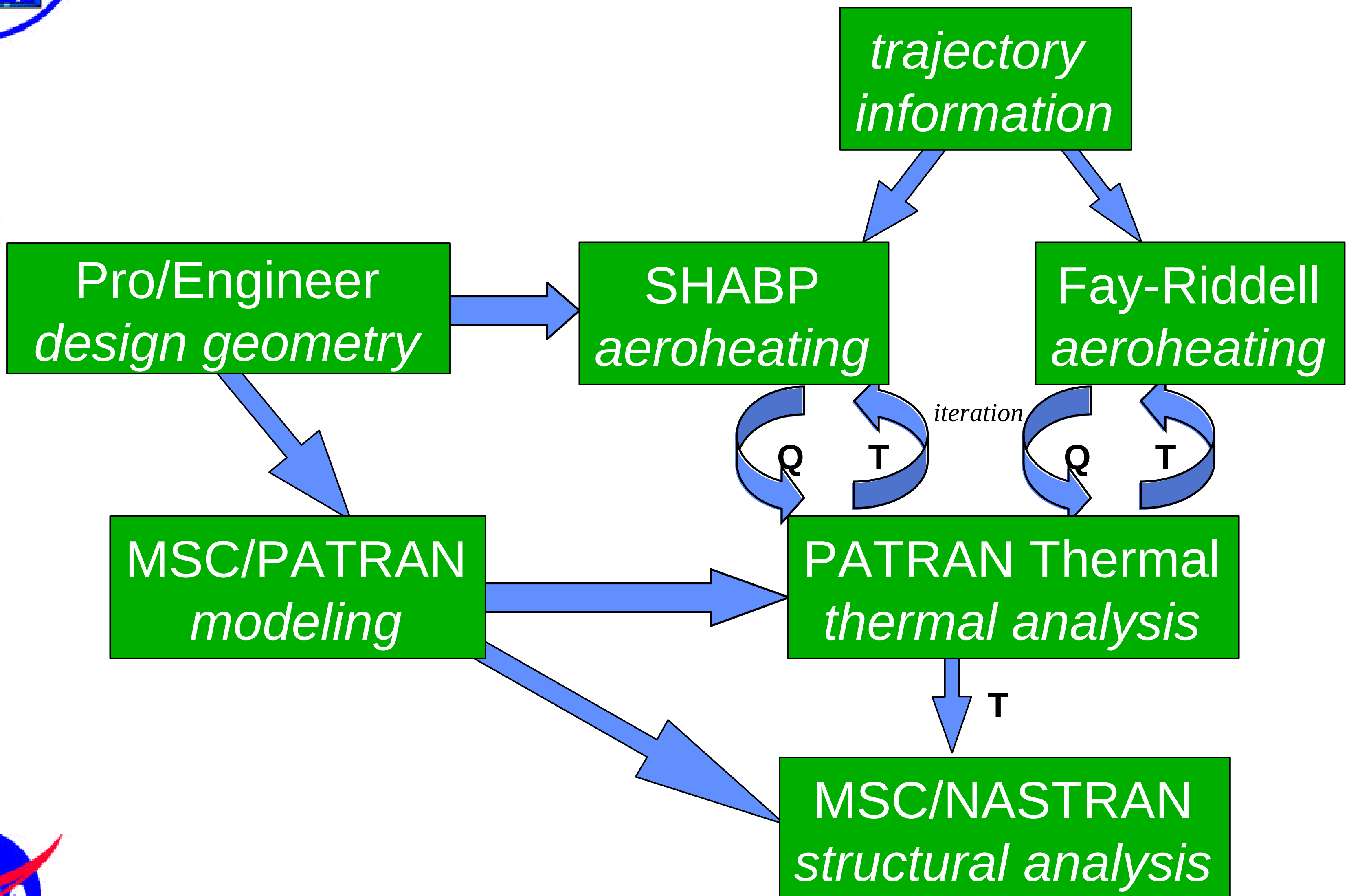


Dryden Flight Research Center EC99-45265-18 Photographed DEC1999
X-43 ground testing.
NASA/Dryden photo by Tom Tschida

Hyper-X Analysis Challenges

- **Hypersonic flight introduces extreme heat loads into vehicle leading edges (wings, tails, and nose).**
- **High temperature materials and coatings are required to distribute heat and carry resulting loads.**
- **Accurate generation and incorporation of heat loads requires tight integration between aeroheating analysis, thermal analysis, and structural analysis.**
- **Loading conditions require nonlinear analysis with temperature-dependent material properties.**

Aero-Thermo-Structural Analysis Process



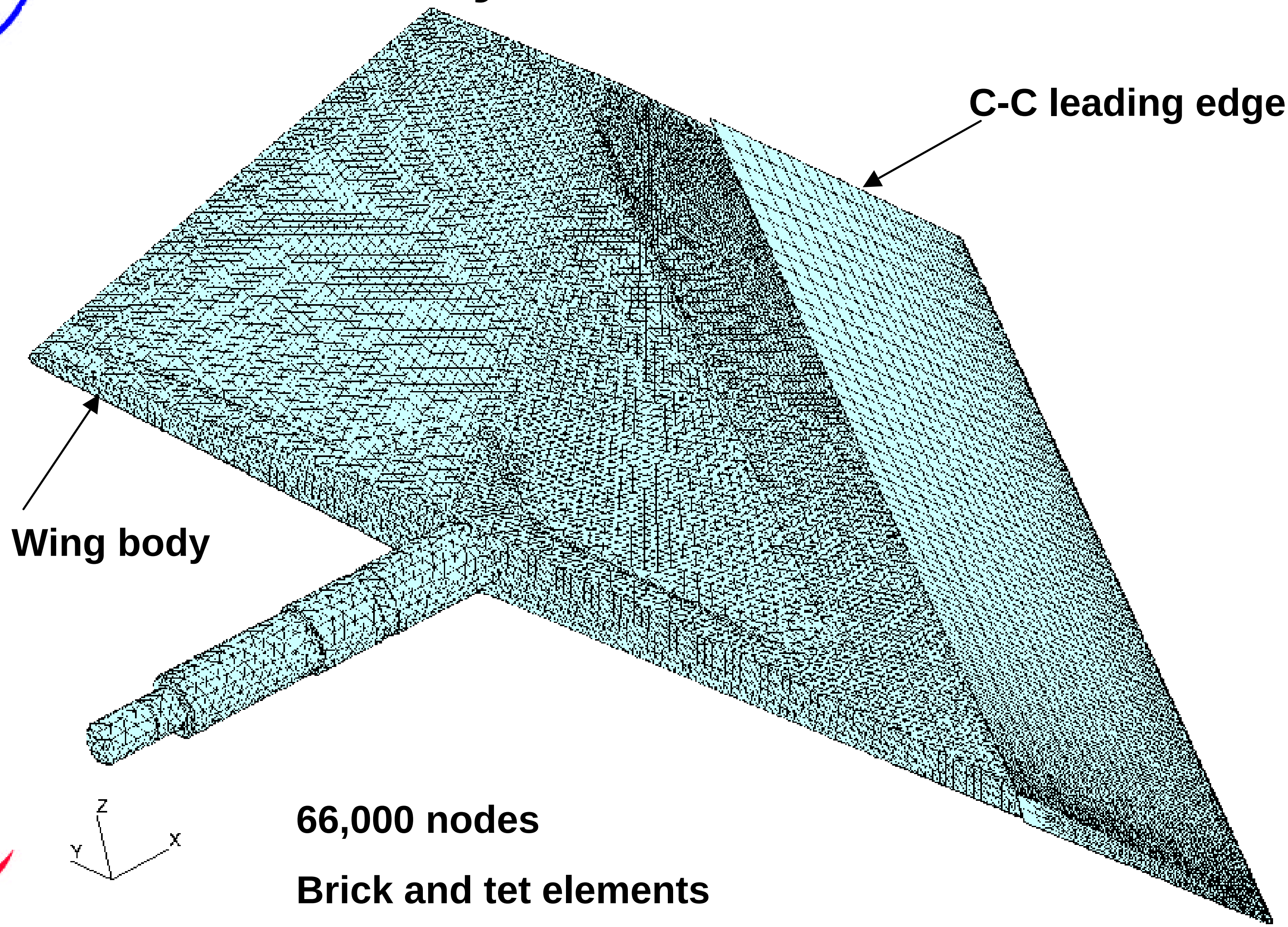
Aero-Thermo-Structural Analysis Process

- **Design in Pro/Engineer**
- **Aeroheating analysis in SHABP from IGES geometry**
- **Import Pro/E model directly to MSC/PATRAN**
- **Thermal analysis in MSC/PATRAN Thermal**
  - Less manual model development due to geometry import
  - Include aerodynamic heating and pressure loads from SHABP
    - Different aeroheating and thermal meshes can be utilized
    - Extensive FORTRAN in PATRAN Thermal to interpolate aeroheating over both time and 3D space
  - Stagnation point heating done using Fay-Riddell
  - Iteration between thermal and aeroheating to capture skin temperature
- **Structural analysis in MSC/NASTRAN**
  - Less manual model building due to sharing with thermal analyst
  - Different thermal and structural meshes can be utilized
  - Uses temperatures interpolated directly from thermal model
  - Nonlinear static analysis performed at discrete trajectory points under thermal and mechanical loads

Thermal Analysis Methods

- **Properties**
  - All properties done as temperature-dependent
  - 3D orthotropic where needed (on C-C)
- **Aeroheating fluxes**
  - On surfaces, aerodynamic heating from SHABP
    - dependent on Mach, altitude, skin temperature, geometry
  - Interpolated in time and space onto PATRAN model
  - On leading edges from Fay-Riddell
    - dependent on Mach, altitude, skin temperature, geometry
  - Factors applied for gap heating, cove heating, etc.
  - Iteration between Q and T to come to closure
  - Uncertainty factor F(time) applied to flux after closure
- **Other boundary conditions**
  - Radiation to atmosphere (changing temperature with descent)
  - Contact resistance between parts and across welds
  - Radiation within cavities
  - All boundary conditions done on geometry to facilitate remesh

Thermal Analysis Model

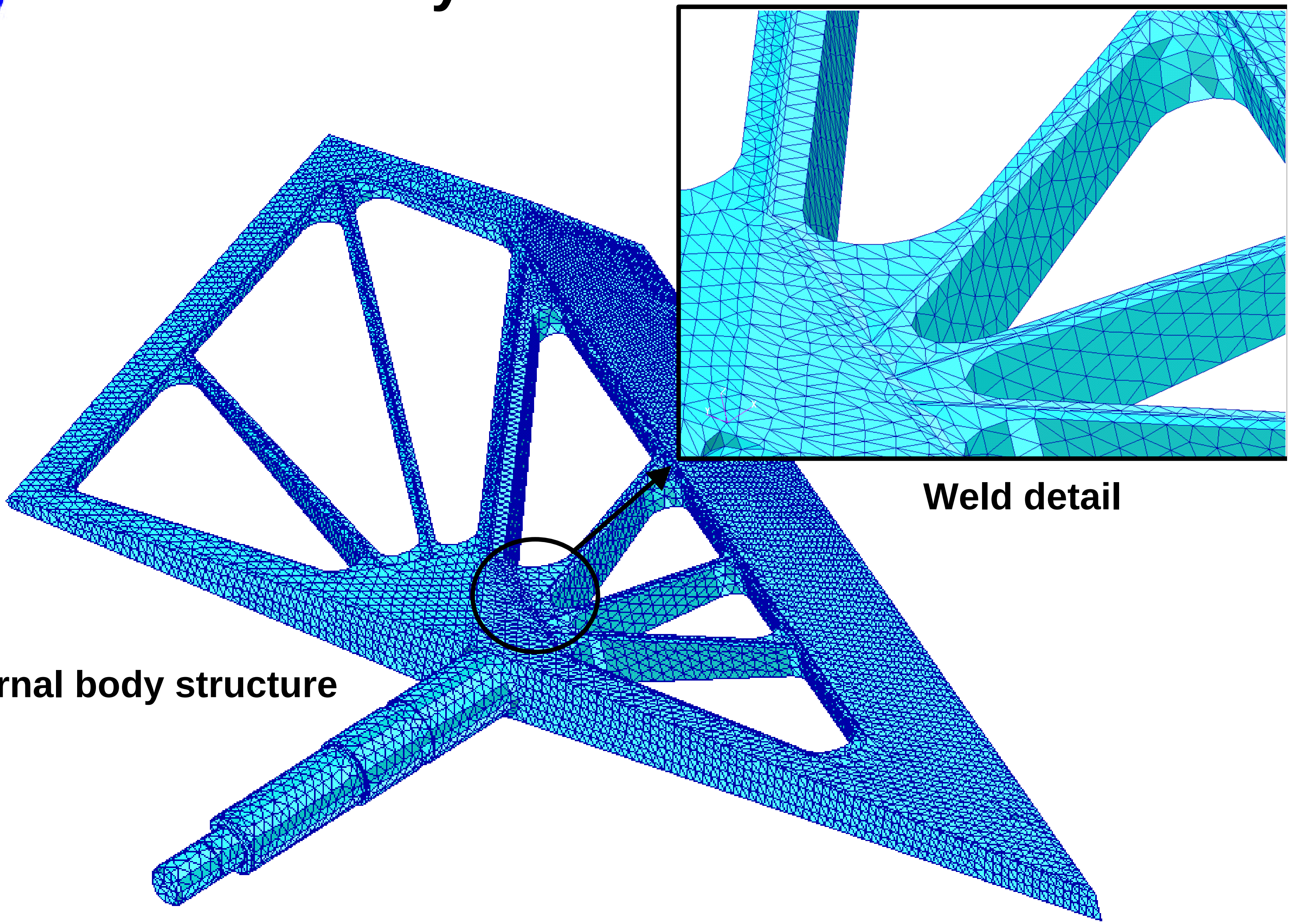


66,000 nodes

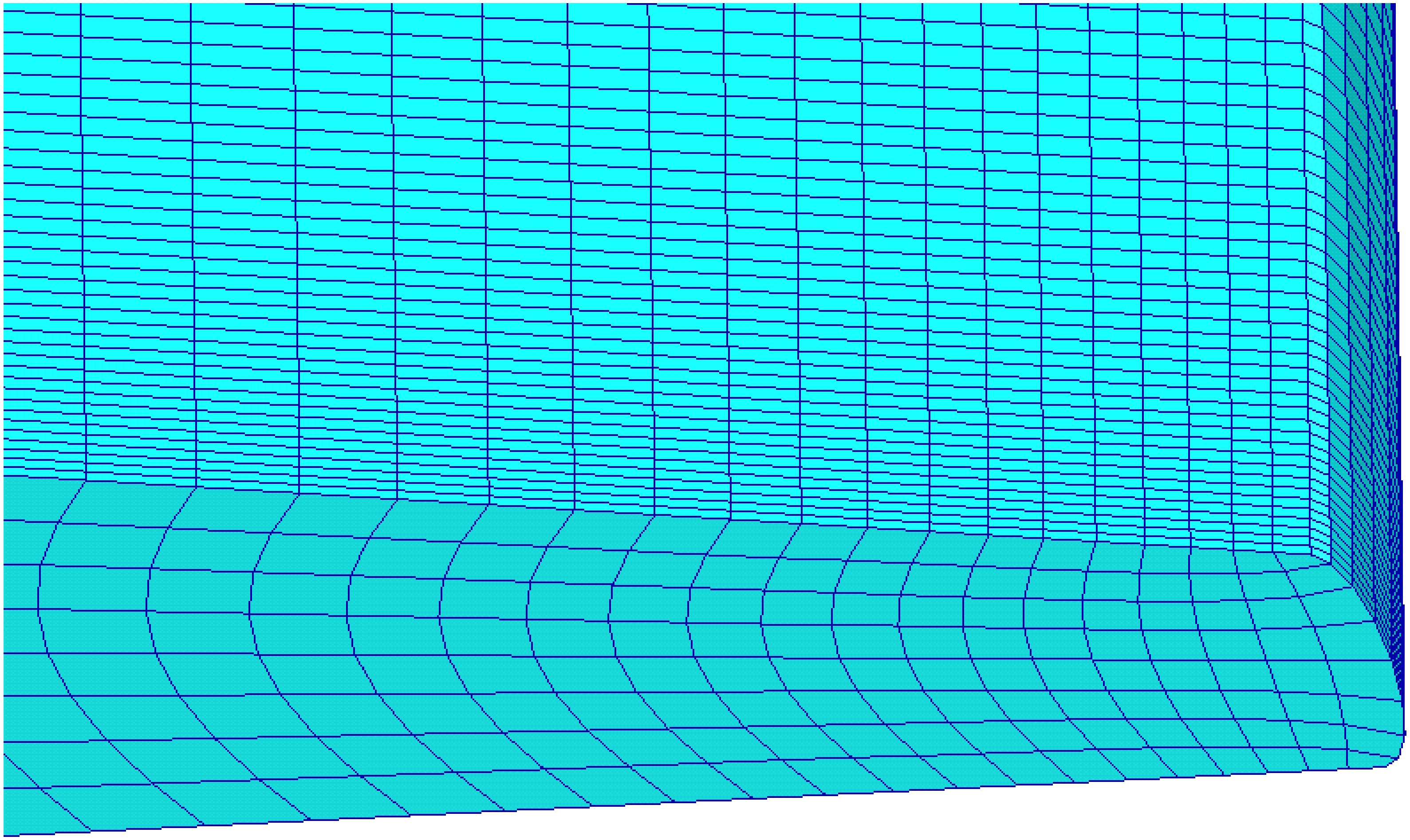
Brick and tet elements

Mesh density at LE 0.1” x 0.1”

Thermal Analysis Model Details



Thermal Analysis Model Details

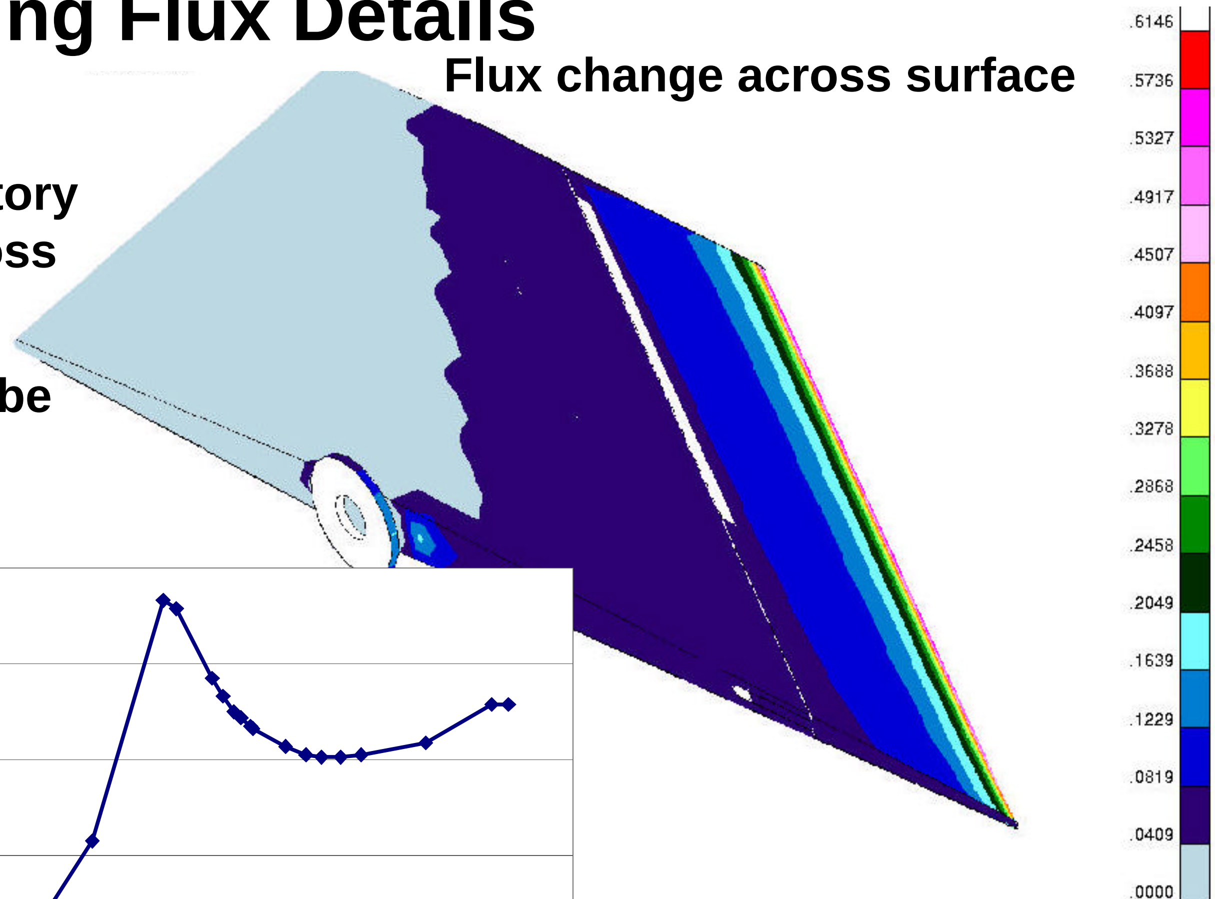


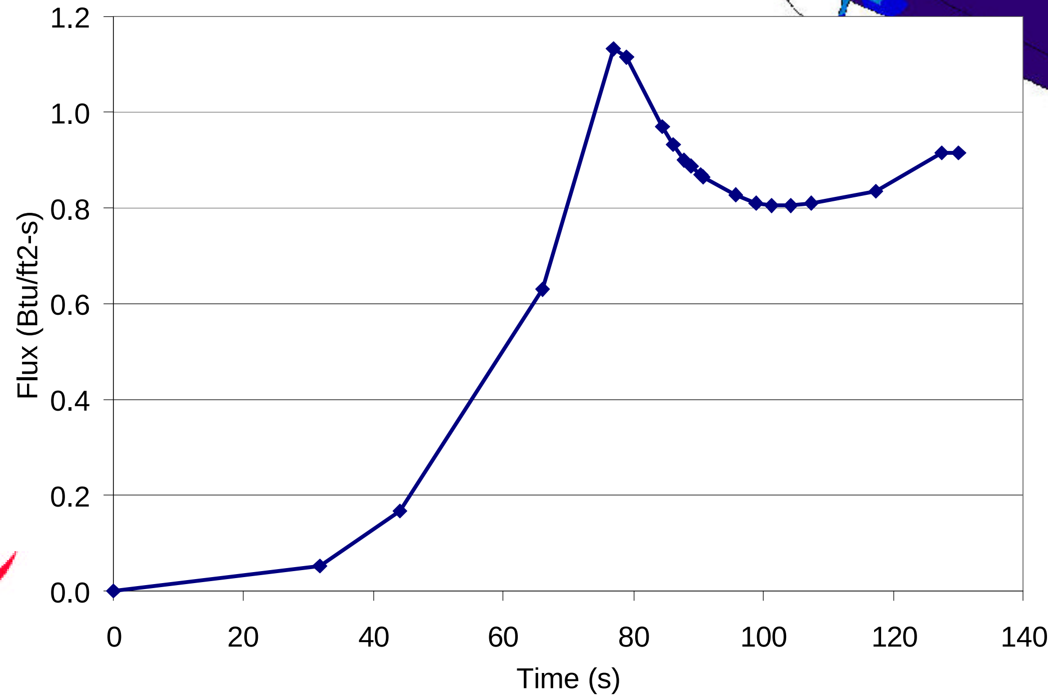
Detail of leading edge mesh

Aeroheating Flux Details

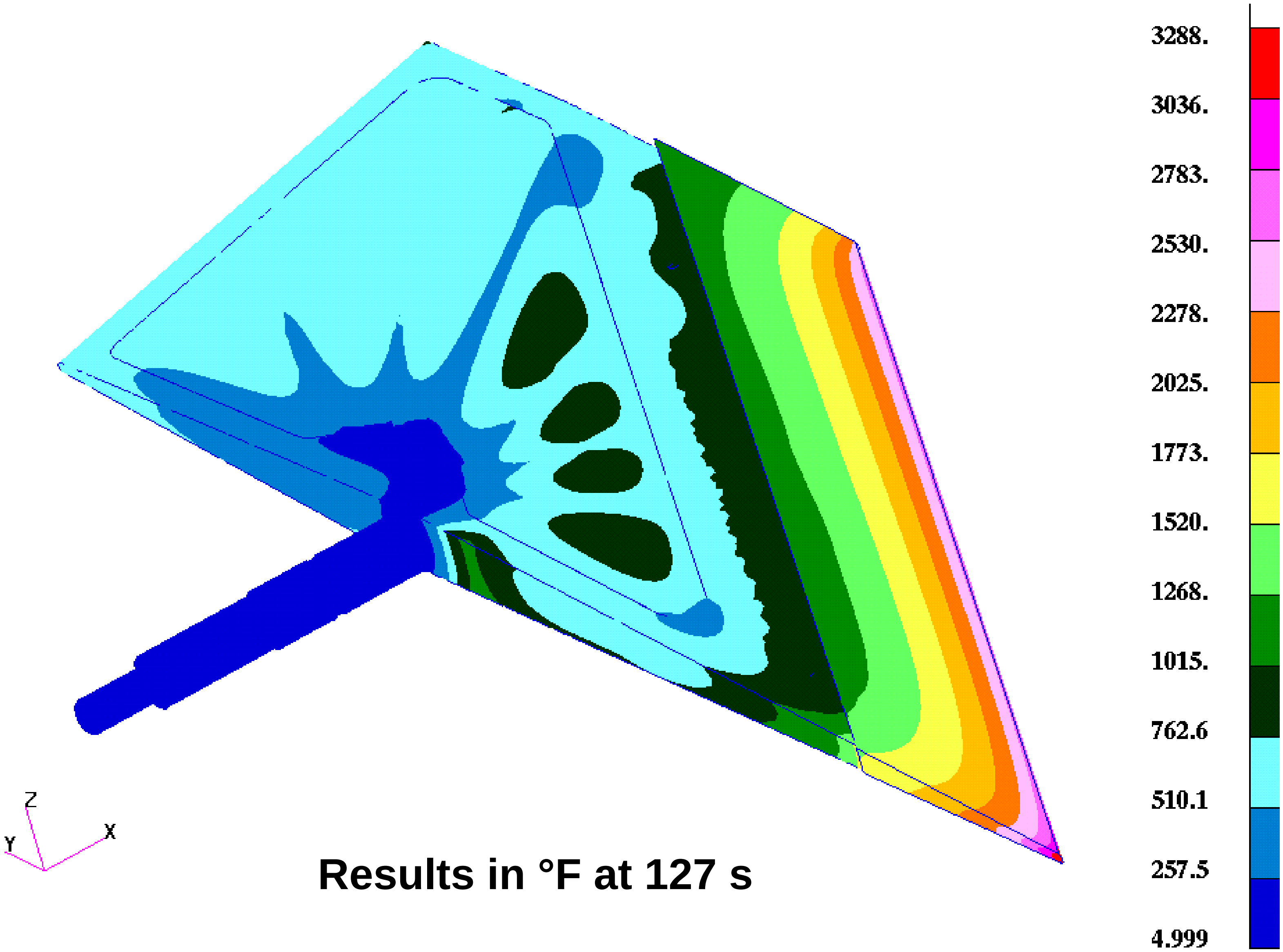
- **At each of 18 trajectory points, the flux across the surface varies**
- **These effects must be combined in the thermal solver**

Flux change across surface



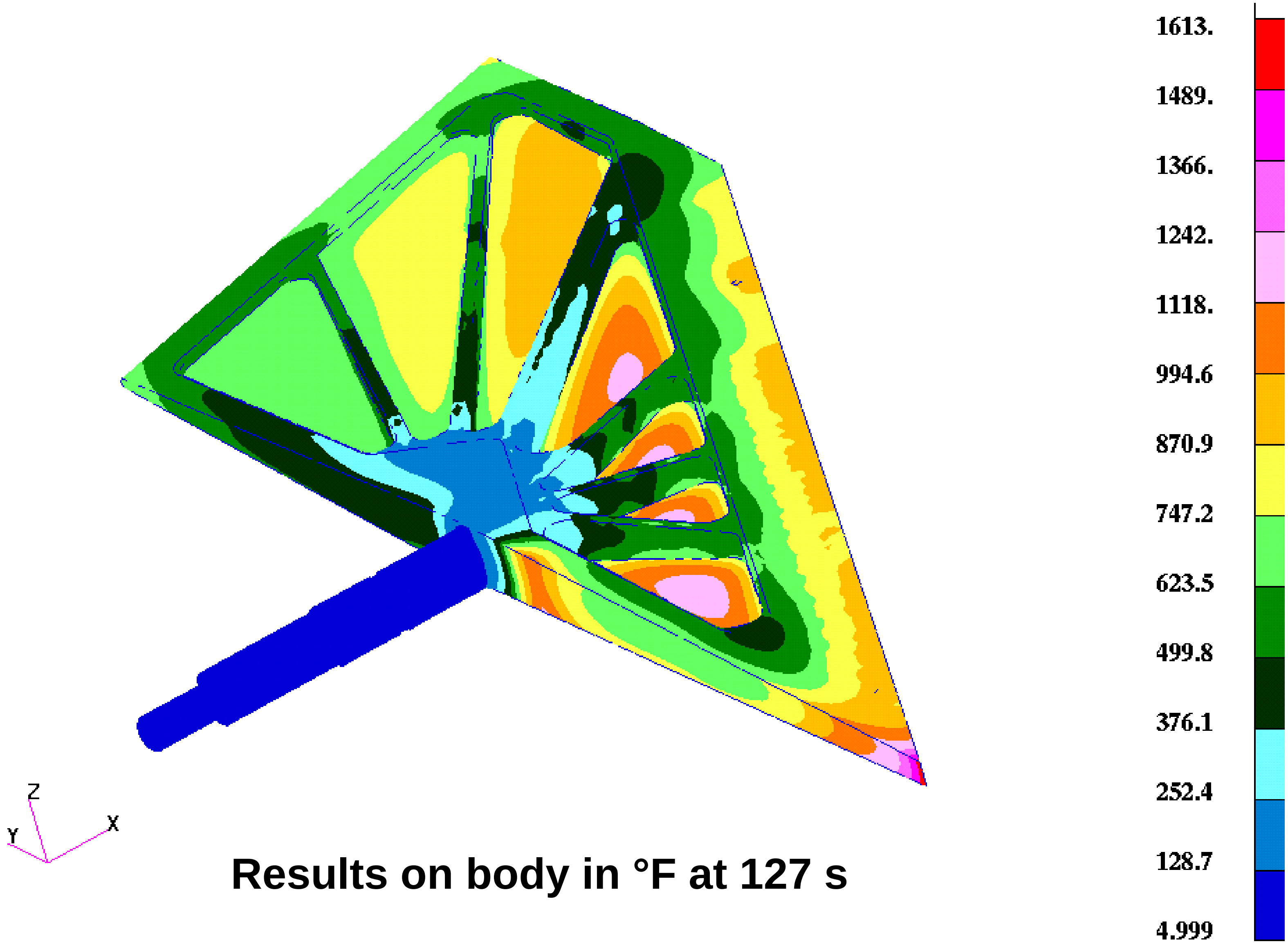


Thermal Analysis Results



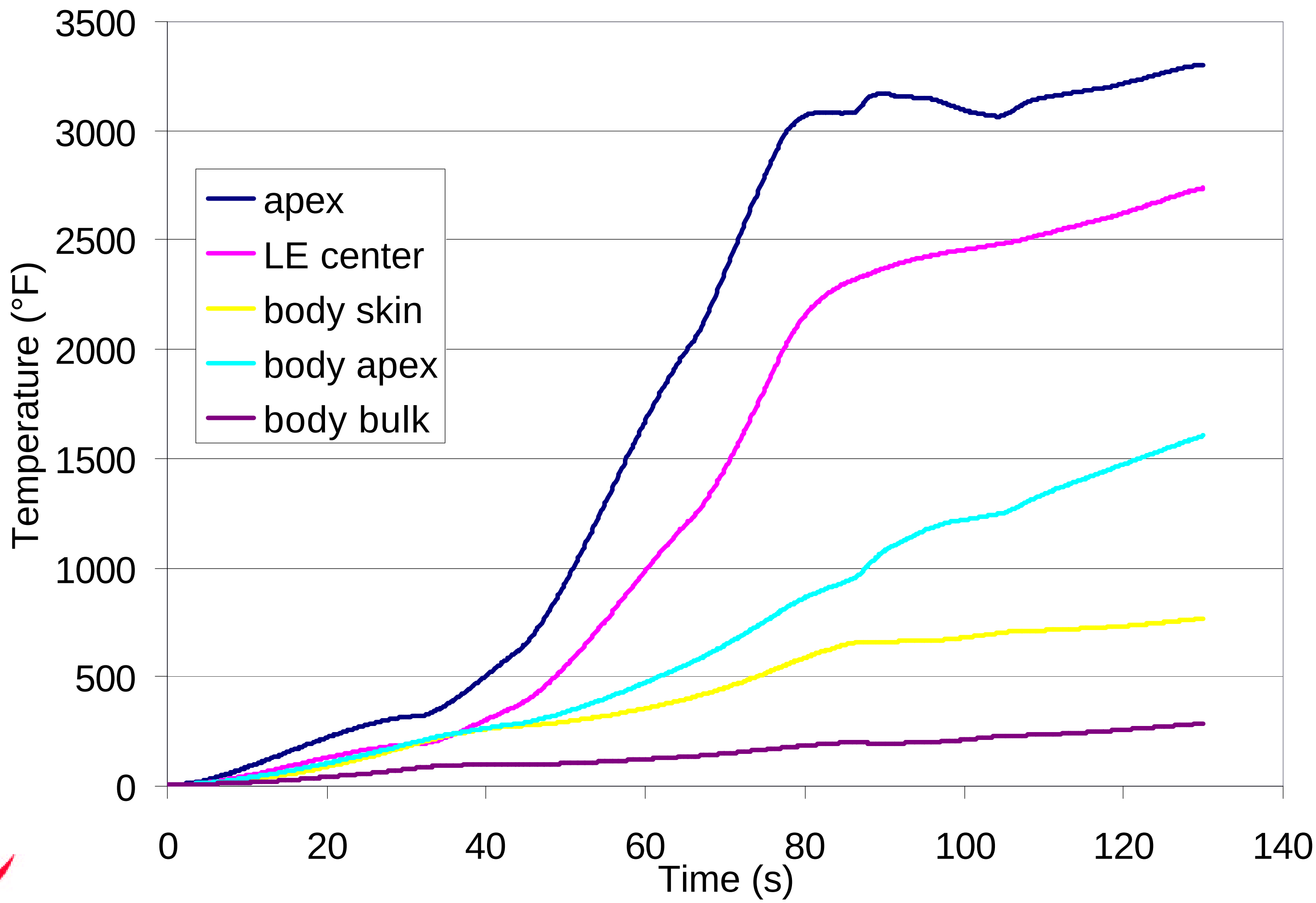
Results in °F at 127 s

Thermal Analysis Results



Results on body in °F at 127 s

Thermal Predicted Transient



Thermal Analysis Results

- **Two outer emissivities run on body with little difference**
  - painted $\varepsilon = 0.8$
  - unpainted $\varepsilon = 0.3$
- **Contact resistance of leading edge varied**
  - 5E-4 to 5E-3 Btu/in^2-s-°F with little effect
- **Contact resistance at weld varied**
  - 0.1 to 1.0 Btu/in^2-s-°F with little effect

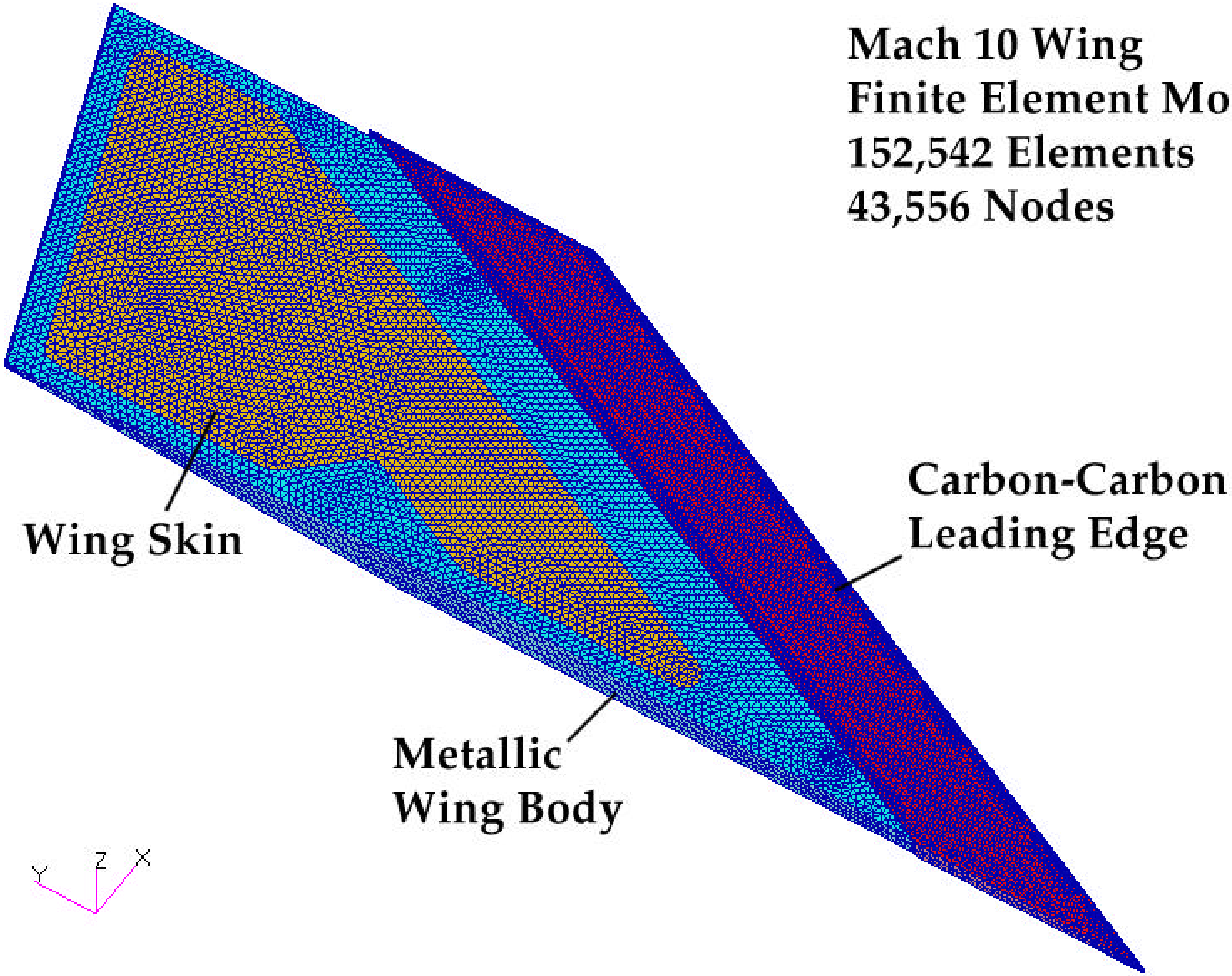
Structural Analysis Methods

- **Temperatures from thermal analysis interpolated through MSC/Patran onto structural finite element mesh.**
- **Analysis performed using MSC/Nastran v70.5.**
- **Initial linear analysis run for yield assessment.**
- **Nonlinear analysis performed using temperature-dependent material properties (elastic modulii and coefficients of thermal expansion).**
- **Temperature-dependent stress/strain curves used in nonlinear solutions for materials experiencing yield.**
- **Discrete trajectory points analyzed to determine worst case loads for strain and deflection (not always the hottest case).**
- **Strain results evaluated in light of short duration, single use conditions.**
- **Deflection results used to specify initial cold clearances.**

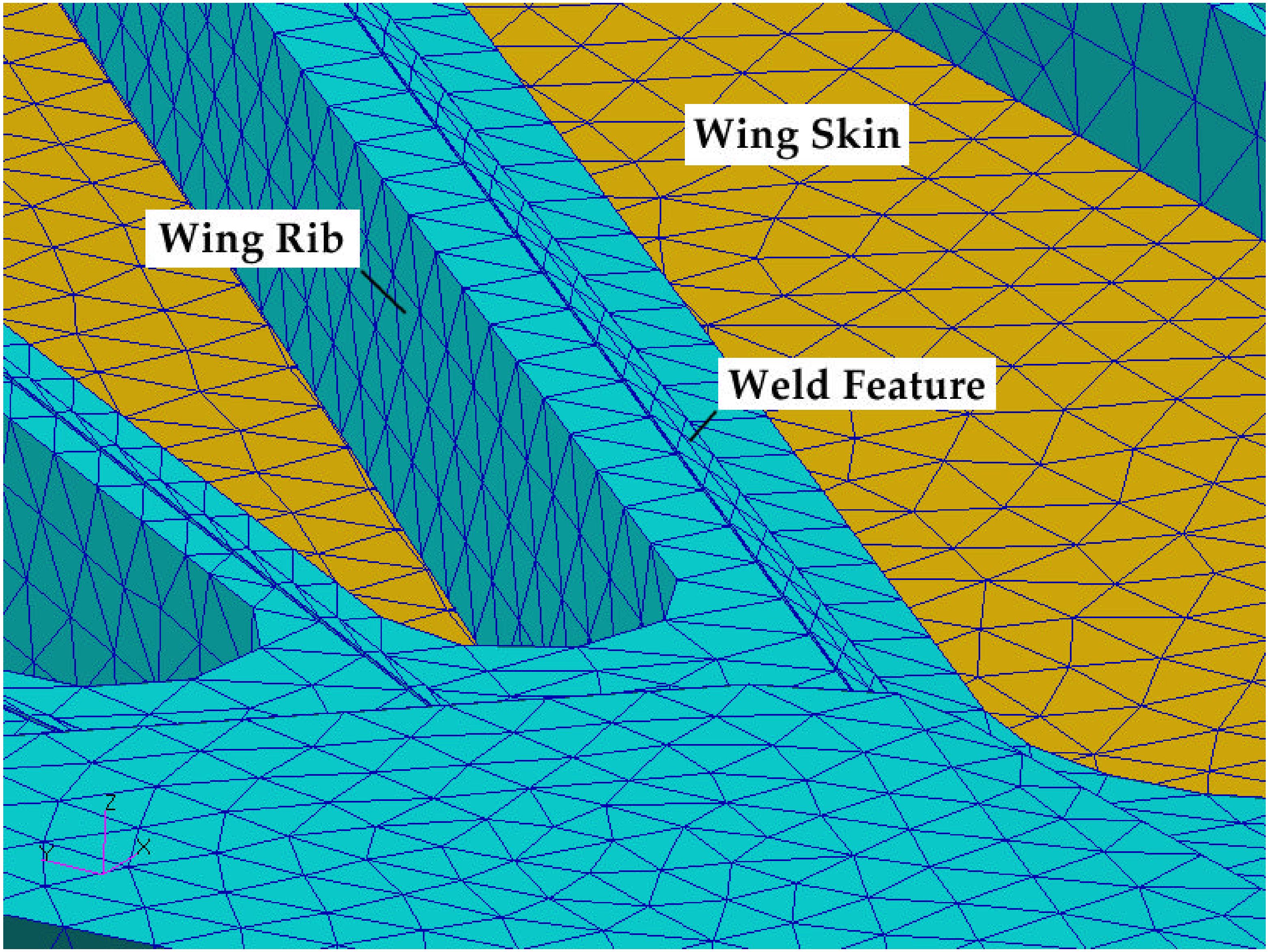
Nonlinear Thermal/Structural Analysis of Hypersonic Vehicle Hot Structures

Mach 10 Wing Finite Element Model

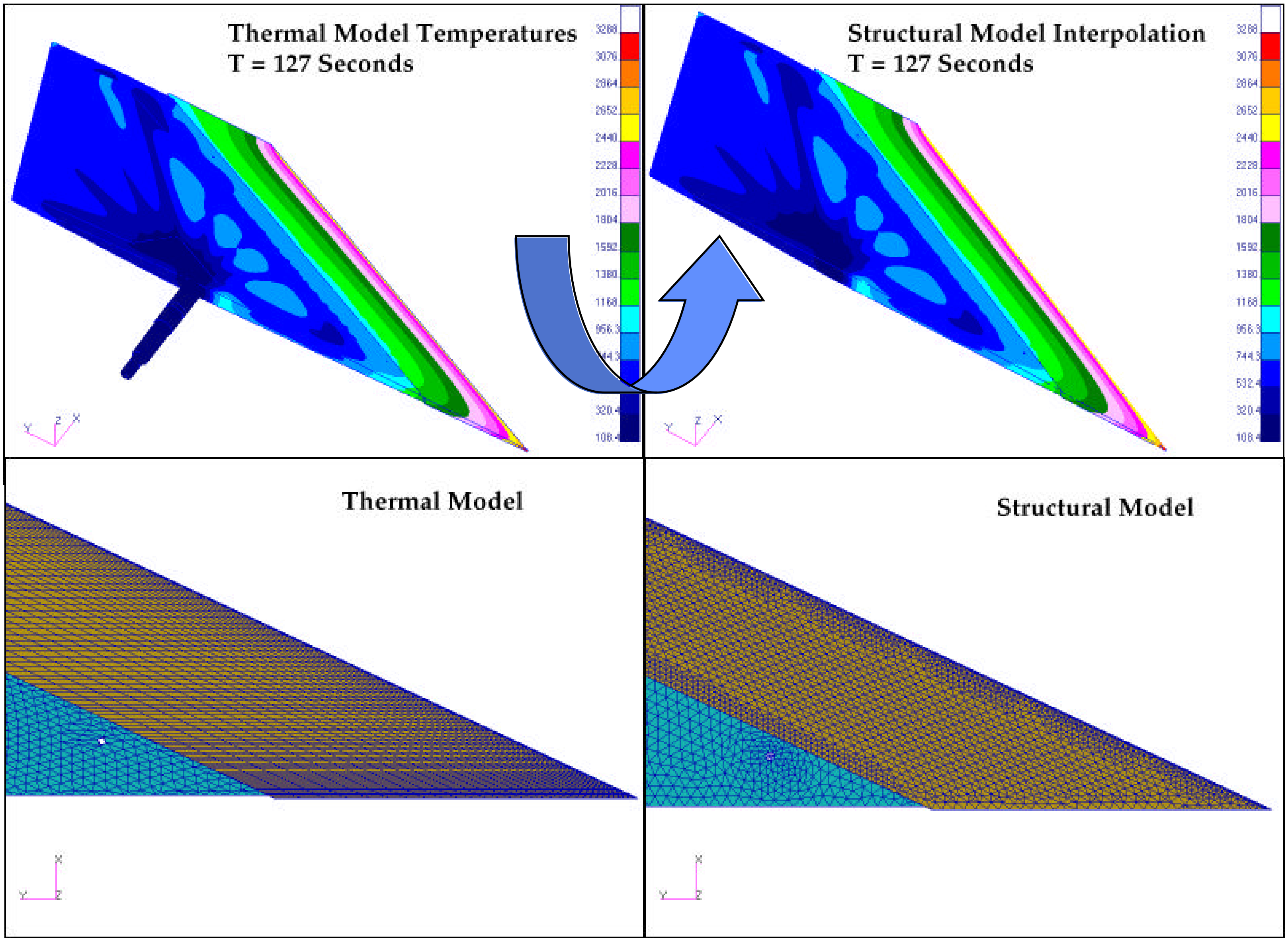
Mach 10 Wing
Finite Element Model
152,542 Elements
43,556 Nodes



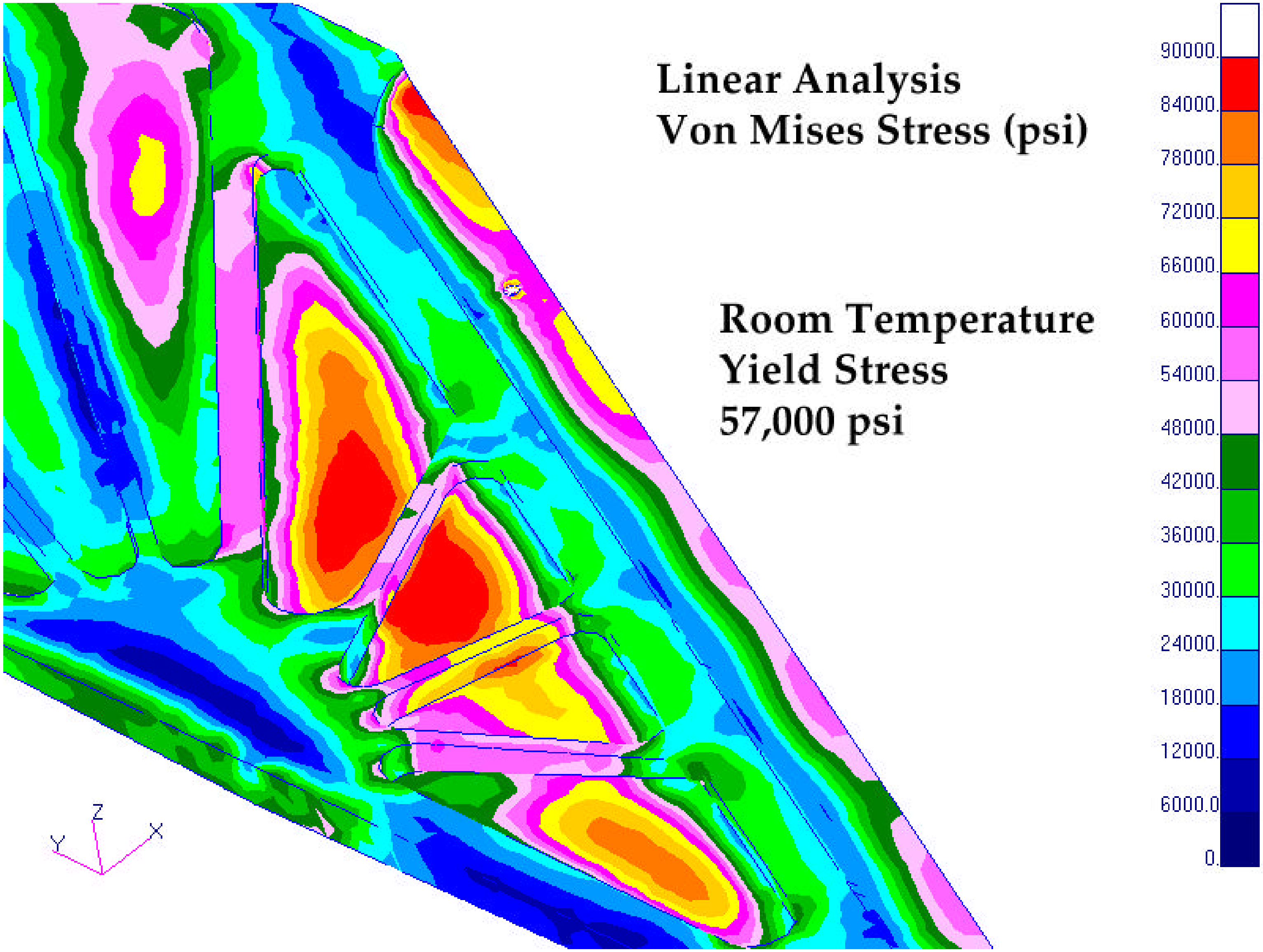
Mach 10 Wing Internals



Thermal/Structural Load Interpolation



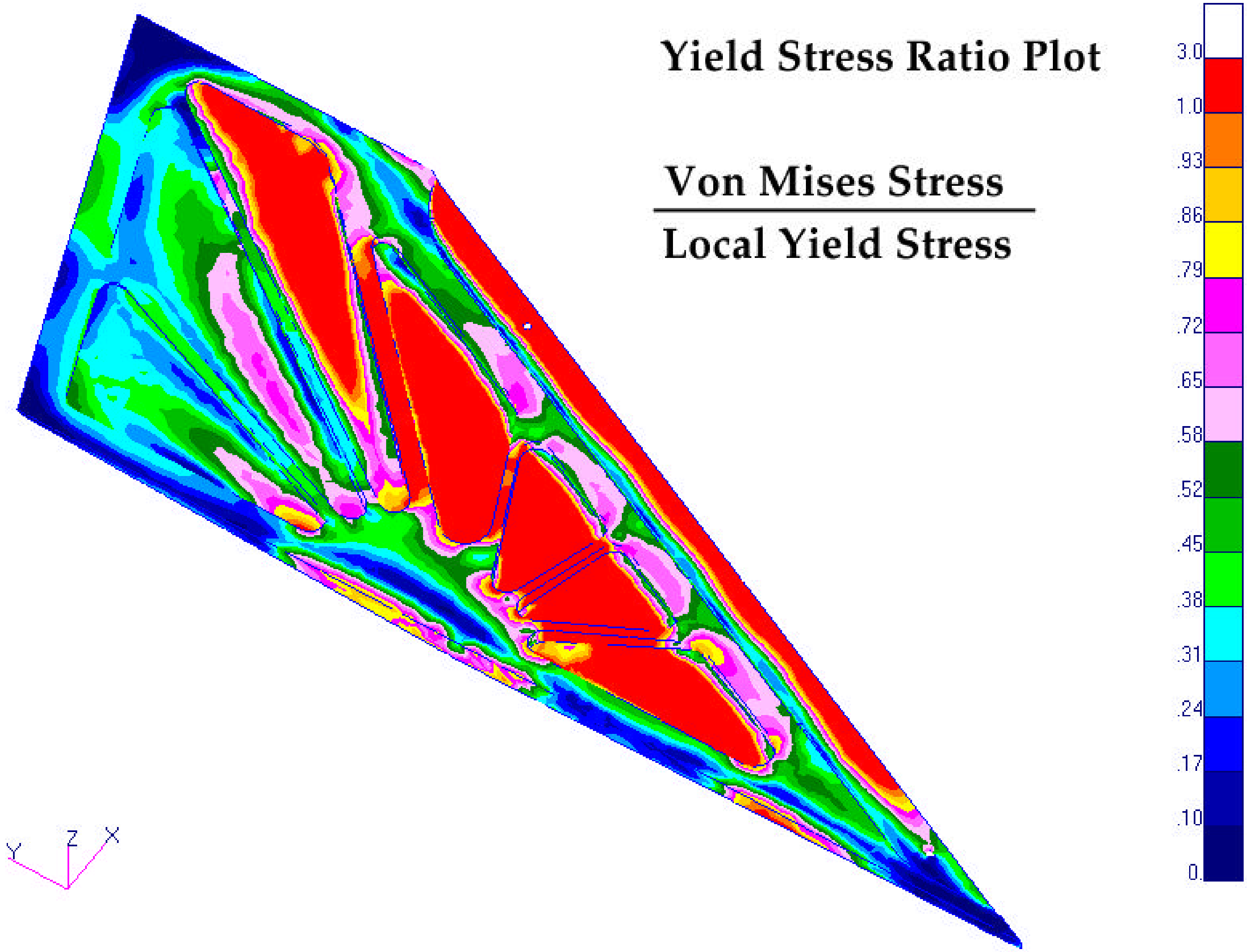
Mach 10 Wing Linear Analysis



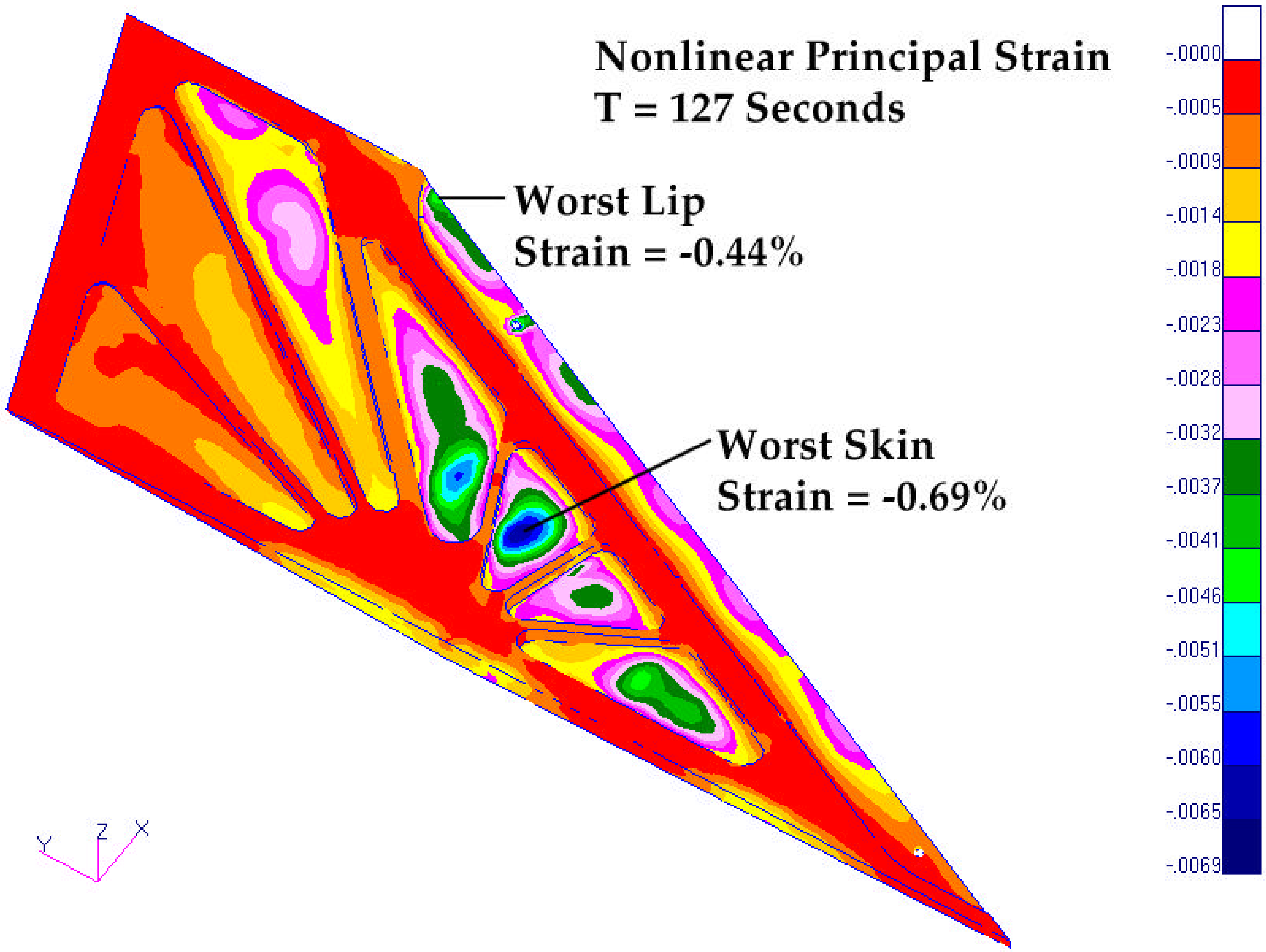
Yield Assessment

- **Problem: How extensive is the yielding? Yield stress is a function of temperature and therefore also a function of position throughout the wing.**
- **Determine an approximate relationship between temperature and yield stress (e.g., piecewise linear), $\sigma_Y(T)$.**
- **Using model temperatures for a given trajectory point, compute the temperature-dependent yield stress at each node using $\sigma_Y(T)$.**
- **Compute the linear Von Mises stress at each node.**
- **Compute the ratio of Von Mises stress to the temperature-dependent yield stress at each node.**
- **Generate a contour plot of the yield stress ratio.**

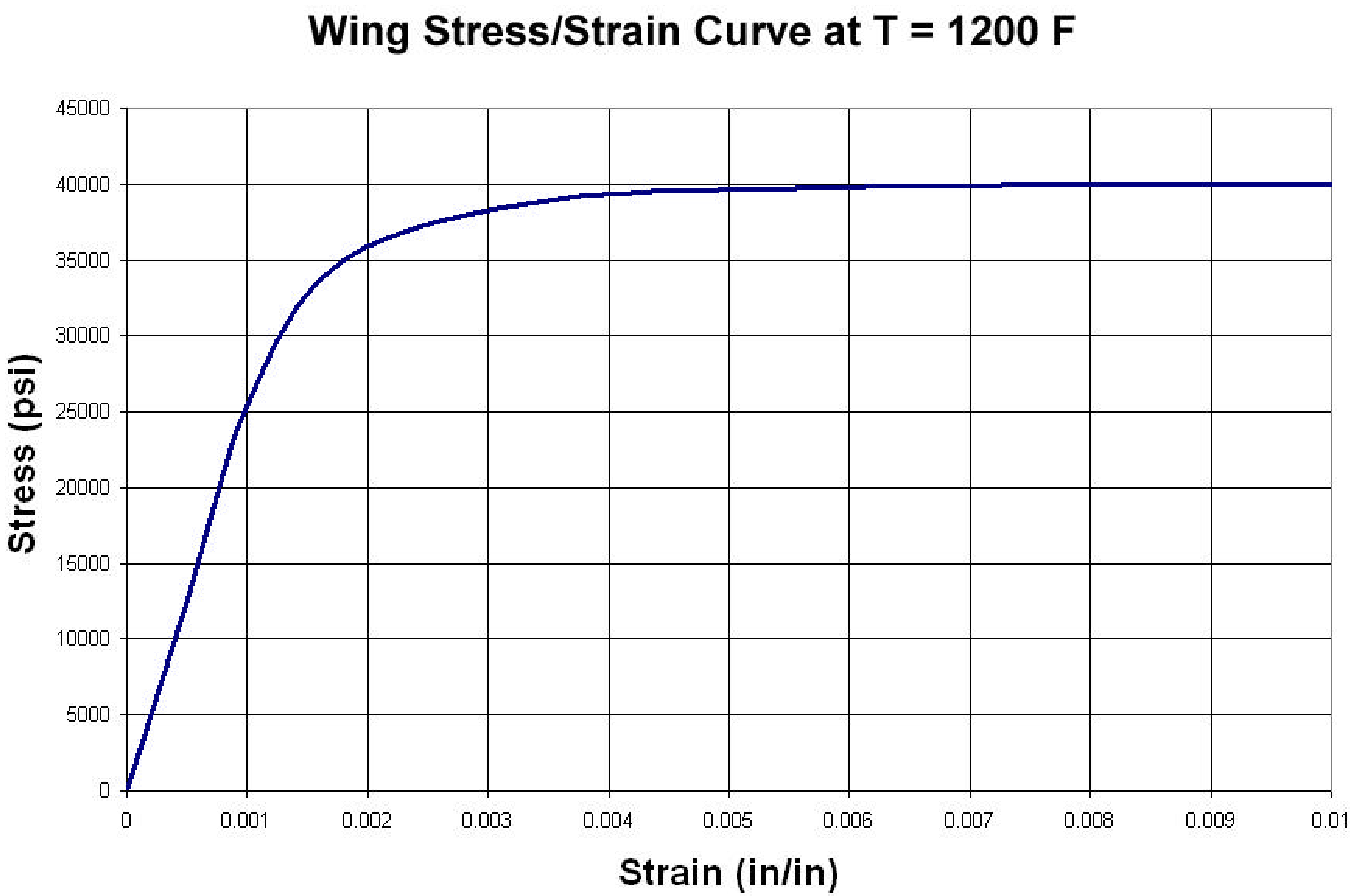
Mach 10 Wing Yield Assessment



Mach 10 Wing Nonlinear Analysis

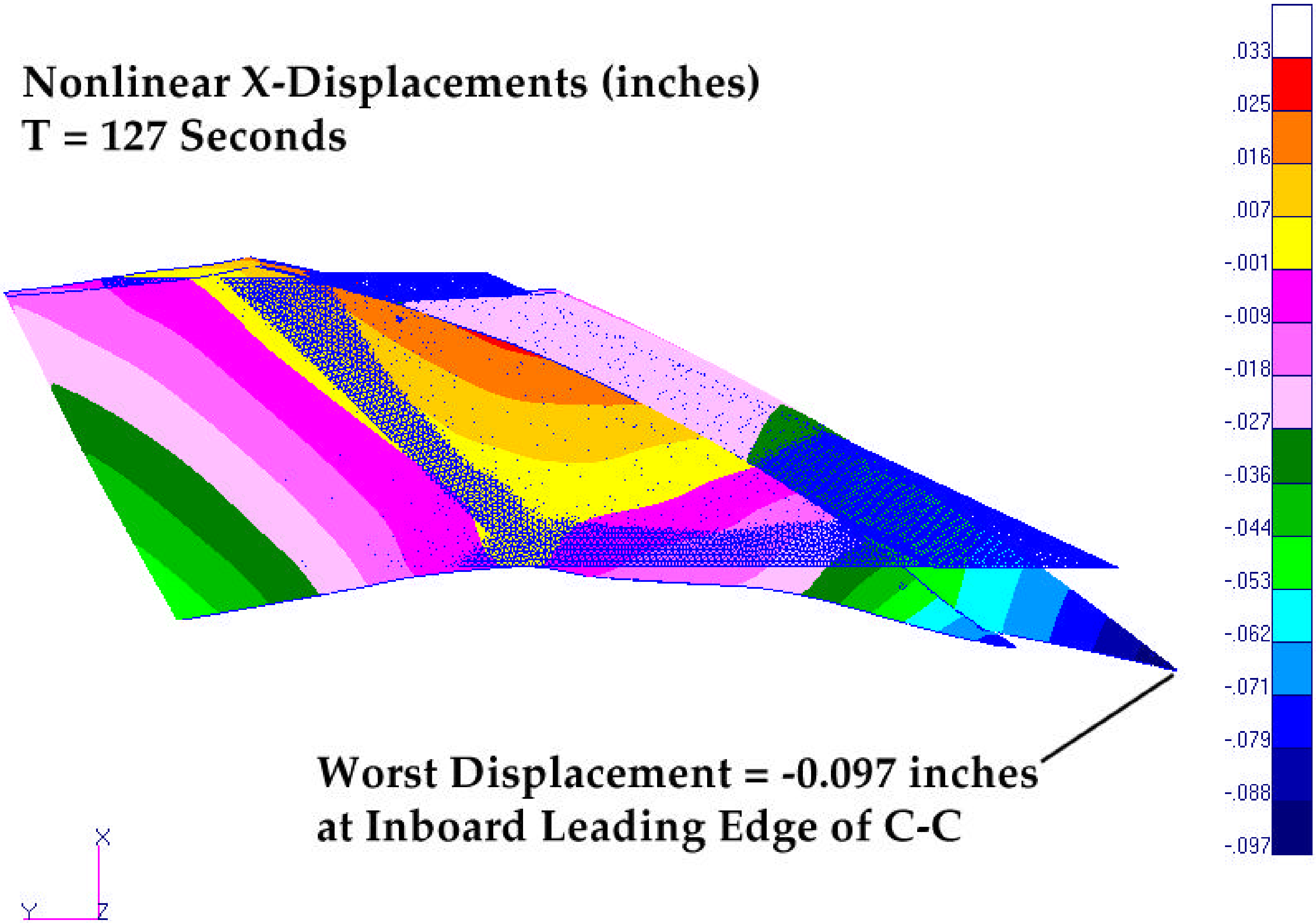


Typical Stress/Strain Curve for Wing



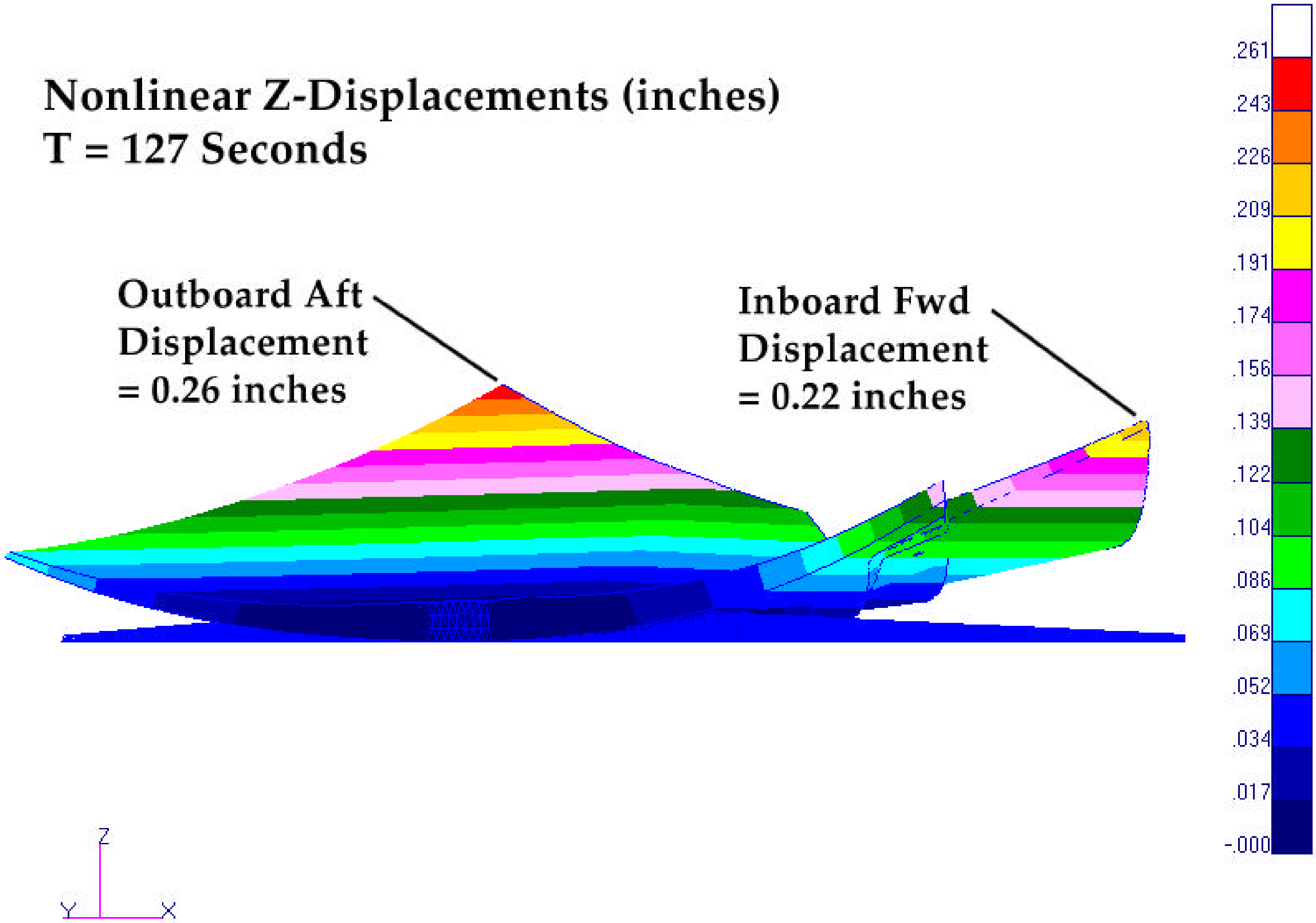
Mach 10 Wing Nonlinear Analysis

Nonlinear X-Displacements (inches)
T = 127 Seconds



Worst Displacement = -0.097 inches at Inboard Leading Edge of C-C

Mach 10 Wing Nonlinear Analysis



Conclusions

- Tight integration of aeroheating, thermal, and structural analyses, each based on full 3-D geometry, was worthwhile and efficient.
- 3-D analysis captured effects that simpler 2-D analysis would have missed.
- Deflected shape from structural analysis can be fed back into aeroheating analysis to assess impact of deformation on flow and heating characteristics.